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SUMMARY OF

A FEASIBILITY INVESTIGATION OF EXPANDABLE STRUCTURES MODULE FOR ORBITAL EXPERIMENT - ARTIFICIAL G

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for

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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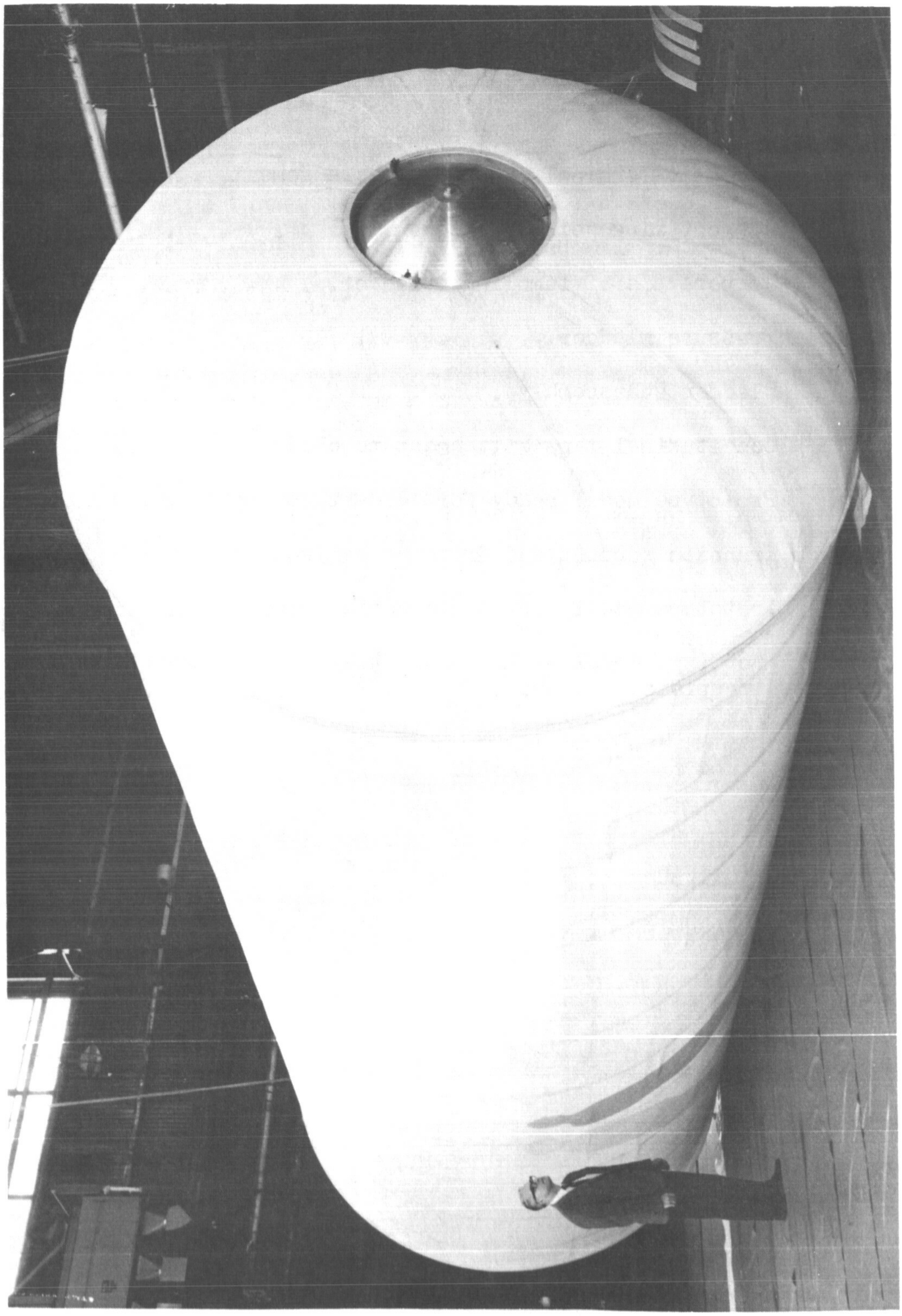

A FEASIBILITY INVESTIGATION OF EXPANDABLE STRUCTURES MODULE FOR ORBITAL EXPERIMENT - ARTIFICIAL G

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SUMMARY

This Summary report covers a six-month effort during which an expandable structures design concept utilizing a flexible materials composite has been investigated. Detailed coverage can be found in the Final Report, Reference 1.

The application was toward a large cylindrical structure, with an inside diameter of 12-1/2 feet and a length of 110 feet, to be used for artificial gravity experiments while in earth orbit.

The work reported includes design of the full-scale model described above, design of a prototype (full diameter but with a 30-foot long straight section), fabrication of the prototype, definition of a test program for the prototype, and design of a canister for the prototype test work.

The design concept on which this program was based is described in the following paragraphs.

The general shape of the structure is that of a 12-1/2 foot i.d. cylinder. The full scale unit has a 110-foot long straight section, with convex ends which make the overall length approximately 117.5 feet. The prototype model is the same except the cylinder portion is only 30 feet long to permit vacuum chamber testing at Langley Research Center (LRC). This general arrangement is shown in Figure 1.

Rigid metal rings are incorporated at appropriate spacing to provide a uniform fold pattern for packaging. Rigid rings are also used at the ends where the deployable unit attaches to its canister. As shown in Figure 1, the packaging is accomplished by application of an axial load while twisting at the same time. This technique causes a "necking-in" of the flexible material between the rigid rings. A 3-foot diameter door is located at each end, and the spacing of the packaging rings does not permit contraction of the flexible structure beyond this dimension. Thus, an astronaut can, if necessary, go through the packaged unit.

The primary structural material used is a special Dacron tape, 2 inches wide which is applied by hand, but in a manner simulating a filament wound

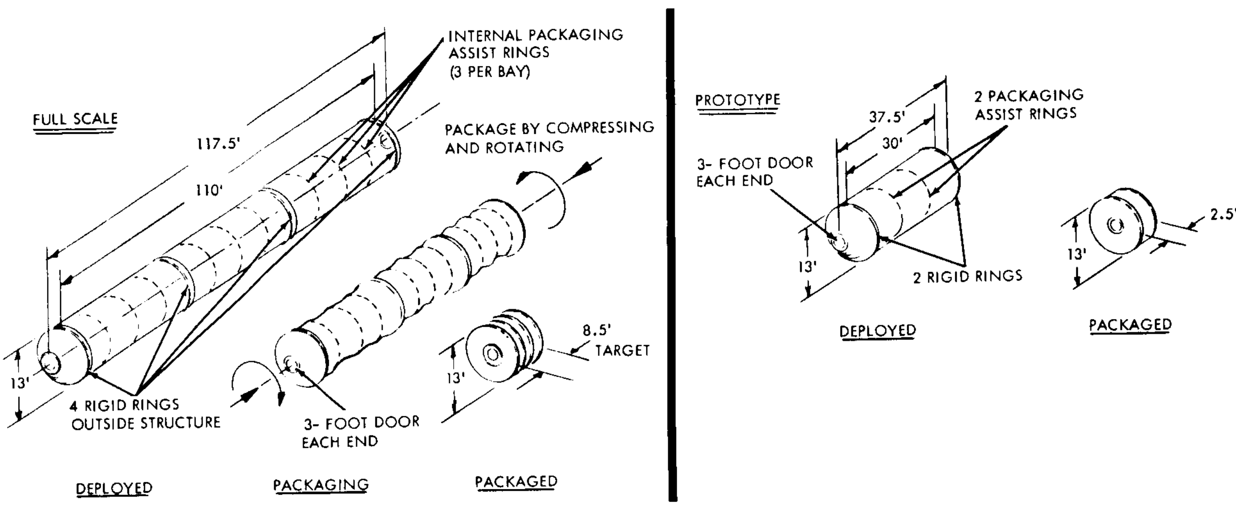

Figure 1. Expandable structure design concept

application. The tape is utilized in both longitudinal and circumferential directions. The circumferential tapes are side by side, and the longitudinals are 2 inches apart. The longitudinals are in effect continuous, running back and forth between 3-foot diameter terminal rings at each end. The circumferentials are also continuous and are applied in a spiral fashion, in the straight cylindrical section only, since the domed ends are tailored to a shape which will result in stress only in the longitudinal direction and need no circumferentials. These tapes are comprised of unidirectional low-twist filaments and therefore provide a relatively high effective modulus, the highest obtainable with Dacron material. The resulting cage-type structure is used to confine a bladder assembly which serves as the seal. This assembly is a special laminate comprised of a nylon fabric-film-fabric layer on the inside, a vinyl foam layer, and an outside nylon fabric layer.

A 1-3/4-inch thick layer of flexible polyurethane foam is applied on the outside of the structure for micrometeoroid protection. Another film-fabric laminate is outside this layer which seals this space to permit squeezing down by evacuating, for packaging purposes. This carries a thermal-control coat of paint on the outside, and also acts as a micrometeoroid bumper.

The above structure is supplemented by miscellaneous hardware items such as external metal rings at the tangent points for canister attachment, end doors and door frames, and several internal rings to facilitate packaging.

The general arrangement described above is shown in Figure 2.

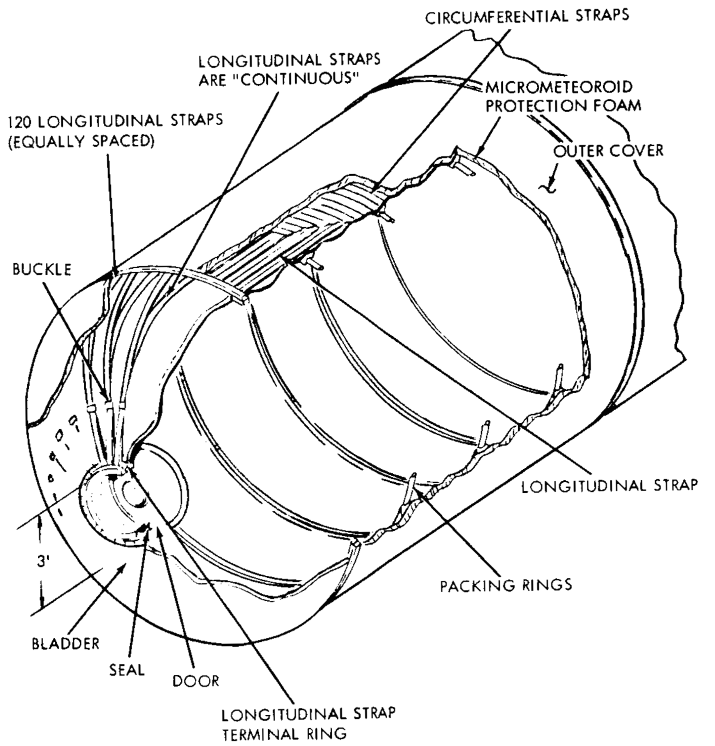

Figure 2. General arrangement - full-scale unit

The task of manufacturing the prototype model was the largest expenditure of this contract. The procedures chosen for fabrication of the prototype were developed to be applicable to a full scale unit.

This fabrication task involved first the manufacture of the Dacron tape, the primary structural material. Approximately 12,800 lineal feet were used on the prototype model. Also, before assembly could be started, the bladder composite material was laminated from the foam, cloth and film-cloth components.

A subassembly of the longitudinal straps was made, and the bladder assembly was made in the flat, after which these subassemblies were joined.

The model was then put in a vertical position for completion of the gore ends. Meanwhile, hardware items were manufactured. This included terminal rings, tangent rings, packaging rings, and doors. These items were installed with the bladder in the vertical position. The model was then placed in a trunnion stand in a horizontal position and the circumferential tapes installed. A preliminary leak test was conducted, after which the micrometeoroid protection foam and the outer cover were installed.

The prototype model was thus readied for packaging which is the first task of the proposed test program.

INTRODUCTION

Under NASA-Langley Research Center Contract NAS1-6673, Goodyear Aerospace Corporation has performed the initial tasks toward "A Feasibility Investigation of Expandable Structures Module for Orbital Experiment - Artificial G". This work has been directed toward a proposed Apollo Applications Program (AAP) wherein a large expandable structure might be utilized in conjunction with Apollo-type vehicles to conduct partial gravity experiments. The vehicle would consist of an erectable cylinder 110 feet long and 12-1/2 feet inside diameter which would be launched in the packaged condition and subsequently rendezvoused with a manned Apollo Command Service Module (CSM). After inflation the system would be tumbled to provide various levels of artificial gravity at various locations along the cylinder. The concept would offer opportunity to conduct biochemical operations, and housekeeping experiments at lunar and other gravity levels using very low rates of rotation. The objective of this contract is the development of a concept for the extendable cylinder. The work hereby conducted included the design of such a structure. A prototype test structure was fabricated full scale in diameter and approximately 37-1/2 feet long. A packaging canister for the prototype was designed, and a test program was defined. A preliminary inflation test was carried out to determine leak rate, and conformance of the geometric configuration with the design specification was carried out.

The period of performance for the work reported herein started 20 September 1966 and concluded 19 March 1967.

TECHNICAL DISCUSSION OF DESIGN

Objective

The objective of this contract effort was to determine the feasibility of deploying and utilizing a large diameter expandable structure as an integral part of a manned earth-orbiting artificial gravity research vehicle by establishing the fabrication techniques, packaging concept, deployment method, and by demonstrating the structural integrity and gas leakage characteristics.

Specific Tasks

Design.

(1) 12-1/2-foot i.d. x 110-foot long expandable cylindrical structure
(2) 12-1/2-foot i.d. x 30 to 40-foot long prototype test module
(3) Canister for prototype testing

Build.

(1) Prototype test module
(2) Miscellaneous composite samples

Design Requirements

Full Scale Model and Prototype.

(1) Operating pressure, 5 psia, Factor of Safety = 3
(2) Permissible leakage, 2% in 24 hr
(3) Micrometeoroid Protection, 0.995 Probability of zero penetration in 14 days at 200 n. mi.
(4) Internal atmosphere, 100% O_2
(5) Thermal control, passive, 70 $\pm$ 20°F
(6) Packageable, deployable in ambient and vacuum
(7) Proof pressure, 7.5 psi, 14 days
(8) Deployment by internal gas expansion
(9) Target package length between tangent points, 1/13
(10) Durable, scuff-resistant inner wall
(11) Provisions for attachment at test end of 500 lb structure to support 500 lb test equipment
(12) To be rotated 4 RPM (2/3 g)

Canister for Prototype.

(1) For ambient and vacuum chamber use
(2) Simulate full scale packaging requirements
(3) Instrumentation provisions for determining packaging loads

Description of Design Concept

The full scale structure is a straight cylinder, 12-1/2 feet inside diameter, with curved ends. The cylindrical straight section is 110 feet long, with the domed ends adding another 3-3/4 feet each, for a total over-all length of 117.5 feet. The prototype model is the same except that the straight section is only 30 feet long (37-1/2 feet over-all). Flexible materials are used to permit packaging of this large structure into a small space. Rigid metal rings are utilized at intervals to provide controlled spacing of the packaging fold locations. Rigid rings are also utilized near the ends where the straight cylindrical section joins the curved ends. These rings also provide points for attachment of the canister.

The primary structural material is a special Dacron tape, 2 inches wide, which is applied by hand but in a manner simulating a filament wound application. The tapes are utilized in both longitudinal and circumferential directions. The circumferential tapes are side by side, and the longitudinals are 2 inches apart. The longitudinals are in effect continuous, running back and forth between 3-foot diameter terminal rings at each end. The circumferentials are also continuous and are applied in a spiral fashion, in the straight cylindrical section only, since the domed ends are tailored to a shape which will result in stress only in the longitudinal direction and need no circumferentials. These tapes are comprised of unidirectional low-twist filaments and therefore provide a relatively high effective modulus, the highest obtainable with Dacron material. The resulting cage-type structure is used to confine a bladder assembly which serves as the seal. This assembly is a special laminate comprised of a nylon fabric-film-fabric layer on the inside, a vinyl foam layer, and an outside nylon fabric layer.

A 1-3/4-inch thick layer of flexible polyurethane foam is applied on the outside of the structure for micrometeoroid protection. Another film-fabric laminate is outside this layer which seals this space to permit squeezing down by evacuating, for packaging purposes. This carries a thermal control coat of paint on the outside.

A three-foot diameter door is included on the centerline at each end. These doors are removable inwardly. The packaging fold pattern is such that a three-foot minimum hole is maintained through the flexible structure when folded. Packaging is accomplished by pressing the ends together while rotating one end relative to the other.

Discussion of Main Structure Elements

Bladder. - The bladder performs the functions of sealing the entire structure from door to door, resisting internal damage from workmen moving about and transmitting pressure load to structural tape elements on the outside of the bladder. The composite used is shown in Figure 3.

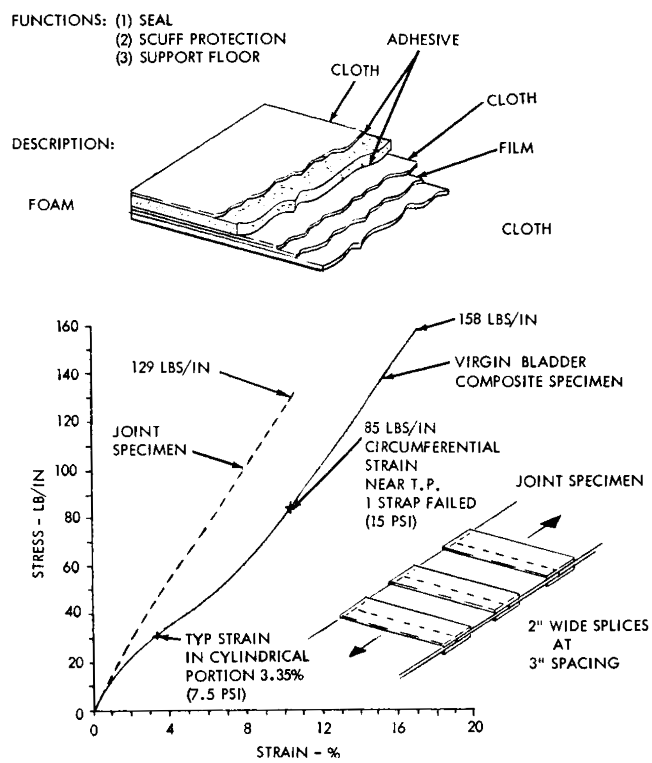

Figure 3. Bladder stress-strain

The seal portion of the bladder composite chosen is a nylon fabric-film-fabric, described in Reference 2. This material has approximately 17 percent ultimate elongation available. It is used in a manner whereby, at the 7.5 psi 14 day proof-pressure test condition, its elongation will be approximately 3.85 percent maximum in the cylindrical region.

The foam used in the prototype model is 1/16-inch thick polyvinyl-chloride (PVC). This layer provides a resilient backing for the seal layer to minimize susceptibility to punctures. The foam is a closed-cell type so that it also acts as a secondary seal behind the film. As a protection for the bladder during handling and to increase bladder joint reliability, a backing layer of nylon cloth is laminated to foam.

The bladder composite material is laminated in panels approximately 3-1/2 x 16 feet. Butt-type joints are used, with a film-cloth tape applied to each side. Tightness of the tape joint on the film-cloth side of the bladder is mandatory. Leakage through such a joint is most apt to occur as a result of a slight wrinkle in the tape or the bladder, thereby providing a path under the tape to the joint. For this reason, a bead of RTV silicone is inserted in the crack between the adjoining panels and allowed to cure after the first film-cloth tape is applied to the film-cloth side of the bladder. This provides a stop for any potential leakage through wrinkles.

Structural Tape. - High tenacity-type Dacron 52 yarn is used for the basic structural material. A very low twist yarn is used to achieve as high effective tensile modulus as possible with this material type. These yarns are made into tape nominally 2 inches wide as shown on Figure 4. The virgin tape so constructed has an ultimate strength of 4390 lb on a quick-break test. At operating pressure of 5 psia, each tape will be loaded to 750 lb.

Stainless steel tapes were also considered, and could be substituted. The advantage to be gained would be noticeably lower elongation, and longer useful life under high load conditions. However, a significant weight penalty would result. The weight comparisons are discussed later in this report.

The relative merits of the Dacron vs stainless steel tape materials, from the standpoint of strength and elongation, are portrayed in Figures 4 and 5.

Tape Splices. - The tape is manufactured in lengths of approximately 900 feet, so few splices are required. A steel "buckle" is incorporated at the splice. The strap members to be spliced are inserted through the buckle and bonded to each other with epoxy adhesive. The buckle ensures that good clamping is maintained. Splice joint strengths are 3900 lb minimum.

Bladder-Type Subassembly. - The construction of this subassembly involves the application of longitudinal and circumferential tapes to the bladder layer. The same tape construction is utilized in both directions. However, since the load level in the longitudinal direction is 1/2 that in the circumferential direction, the longitudinal tapes are applied 2 inches apart. In the end regions beyond the tangency point where the cylindrical section meets the curve, no circumferential tapes are used. Due to the 2-inch space between tapes, the bladder is unsupported locally in these regions. Adequate elongation is available in the bladder composite to permit it to span the gap between straps. However, a simple modification to the design could completely eliminate this condition. The longitudinal straps could be made the same width but with 1/2 the weight now used, and applied over the entire surface. No unsupported bladder would then exist. The penalty would be a weight increase due to the additional adhesive, and the additional cost of making and installing the additional length of longitudinal tape.

Attachment of tapes to bladder is by RTV silicone applied in a sinewave-type pattern over the entire length of tape.

Strap Terminal Rings. - The longitudinal straps are in effect continuous. A steel ring, 3 feet in diameter, 1-1/8-inch diameter cross section, is

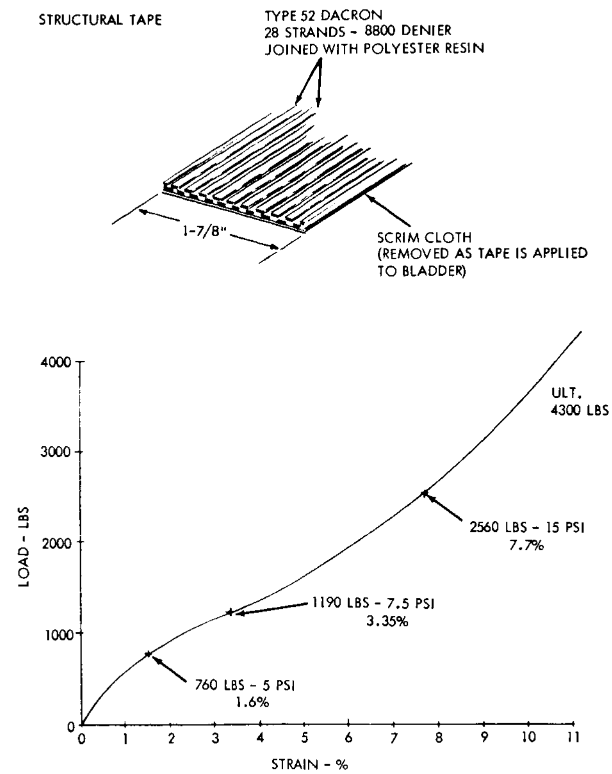

Figure 4. Load-strain Dacron tape

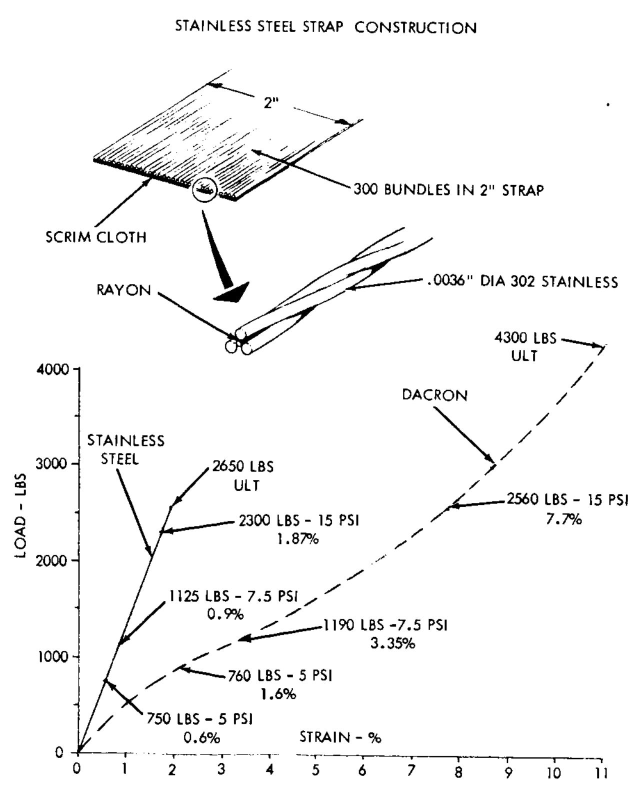

Figure 5. Load-strain comparison of Dacron and stainless steel straps

inserted at each end. The longitudinal strap goes back-and-forth from ring to ring. Thus, the load from each strap loop is carried by the ring. The rings are made in halves to permit insertion into the strap loops. The ring halves are joined by a threaded fitting. The ring halves have female threads in the ends and are joined by a male fitting with a left-hand thread on one end and a right-hand thread on the other.

The strap-to-terminal-ring joint arrangement is schematically shown in Figures 2 and 6.

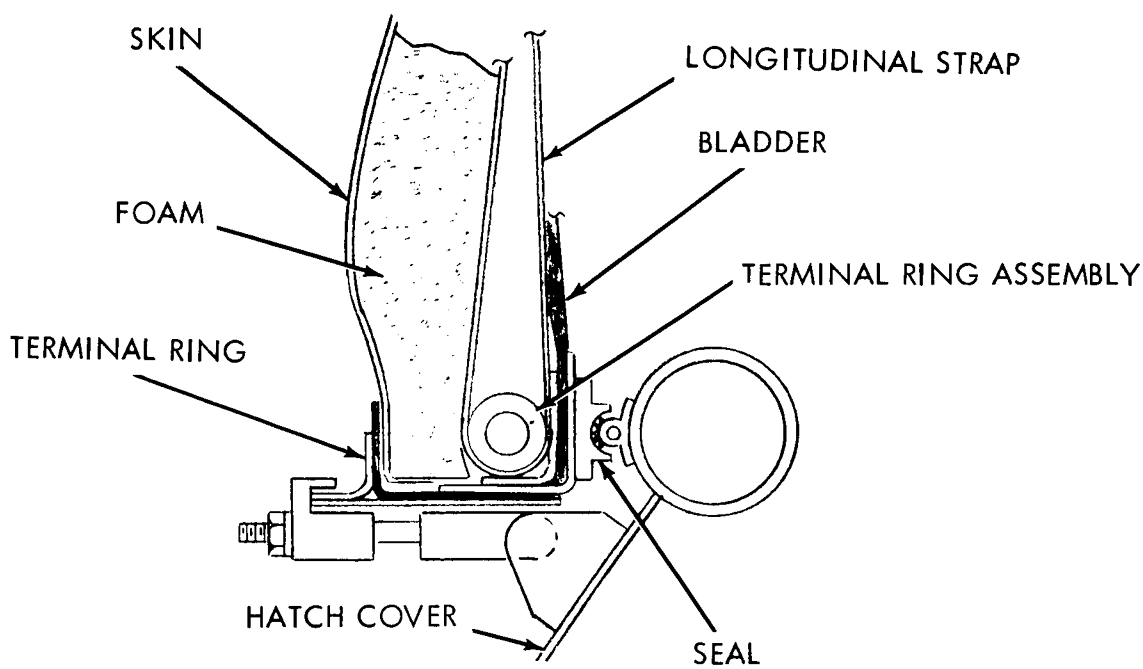

Figure 6. Strap-to-terminal-ring joint arrangement

Tangent Rings. - Figures 2 and 7 depict the arrangement in the region where the contoured ends meet the straight cylindrical section. Three-inch square cross-section aluminum rings are attached to the outside of the structure in these regions. These rings provide hard attach points for the canister and also control the primary fold locations in the end regions, and act as manifolds for the evaluation of the wall of the structure prior to packaging. Attachment of these rings to the soft structure is made prior to application of the circumferential tapes. This is accomplished by bonding short lengths of the Dacron tape material to the longitudinal straps and the rings (see Figure 7).

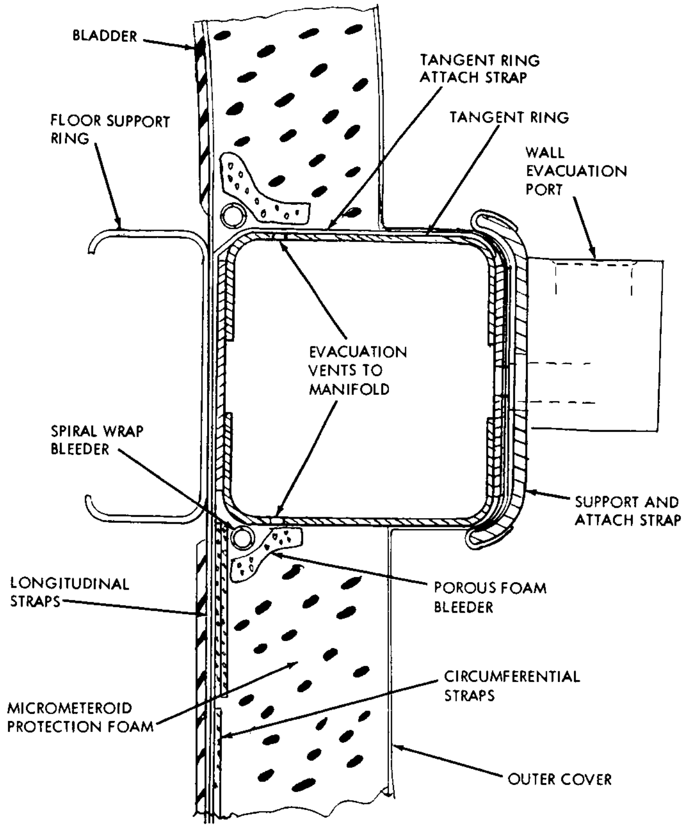

Figure 7. Tangent ring joint

A 3-inch wide aluminum channel ring is inserted on the inside of the bladder at these tangent locations. RTV silicone is used as a bonding agent. The function of these rings is to provide structure to which a floor could be attached when implemented for an artificial gravity experiment.

Bladder Terminal Rings. - Since a 3-foot diameter door is incorporated into each end of the structure, a framing of this door is required. This provides a place to terminate the bladder, and to mount the door seals (see Figure 6). The arrangement used provides two aluminum angles with the bladder end sandwiched between. Sealing and bonding of this joint is accomplished with RTV silicone.

Doors. - A 3-foot diameter aluminum spun door with a spherical radius is located at each end. One of these doors has an 8-inch diameter acrylic window in the center and ports for pressure line attachment and instrumentation wiring insertions. An annular tube frame is attached by welding.

Loose fitting latches are attached to these doors for the test article. These provide means of holding the door in position snugly until the internal pressure exerts enough force on the door to effectively mate the seals.

Packaging Rings. - Packaging is to be achieved by compressing the unit endwise, while rotating one end on its axis in relation to the other end. Twisting one end relative to the other causes a "necking-down" between the rigid tangent rings. By incorporation of additional stiff rings at appropriate length-wise locations, the contraction inwardly can be limited to retain an opening from one end to the other while in the packaged condition. For the test article, two such rings are used. Thus, the 30-foot length between tangent rings is divided into three 10-foot increments for packaging.

These rings are of 3-inch diameter aluminum tubing. Attachment to the bladder is complicated somewhat by the fact that the bladder will elongate when pressurized. Therefore, if rigid attachment were made between the rings and the bladder it would result in a restriction of the bladder elongation, and would put undesirable local loads into the bladder. This problem was overcome by use of flexible foam for this attachment. A foam annular ring of rectangular cross-section is placed between the ring and the bladder. The rings are attached to the foam by straps. Under no-load condition the foam is compressed. As internal pressure is applied, the structure expands, and the foam expands to make up the difference in diameter between the ring and the structure.

Weight

The calculated weights of the full-scale structure and the prototype model are tabulated in Table I. These weights are based on the engineering designs now complete and the amounts of adhesives utilized in fabrication of the prototype model.

An alternate design utilizing longitudinal strap material 1/2 as heavy as shown in the designs, but completely covering the bladder, would increase the total adhesive requirements. A comparable prototype weight would then be 1725 lb compared to 1622 lb for the existing model. Comparable full-scale unit weights would be 5511 lb for Dacron strap type and 6196 lb using stainless steel for strap material.

The weight of the adhesive system shown for attachment of straps is maximum and measurable reduction in this weight should be attainable with optimum design.

The material composite used for the prototype model weighs 0.815 lb/sq. ft. The comparable structure if stainless steel were used would weigh 0.955 lb/sq ft. These numbers would be increased to 0.875 and 1.015 respectively if lighter longitudinal tape were used over the entire area.

TABLE I - WEIGHT SUMMARY - STRUCTURE

Structure	Weight - Lb		
	Prototype	Full Scale	
		Dacron Straps	Stainless Straps
Hard Structure			
External Tangent Rings (2)	112	(4) 224	224
Internal Tangent Rings (2)	40	(4) 80	80
Strap Terminal Rings	40	50	50
Door Frames	9	9	9
Doors	20	20	20
Packaging Rings (2)	56	(9) 253	253
Attachment Straps (2)	48	(2) 48	48
Subtotals (A)	335	684	684
Flexible Structure			
Bladder	168	830	830
Longitudinal Tapes	140	370	625
Circumferential Tapes	170	620	1050
Micrometeoroid Foam	275	835	835
Outer Cover	100	303	303
Interlayer and Seam Adhesive	434	1449	1449
Subtotals (B)	1287	4407	5092
Total - (A) + (B)	1622	5091	5776

Structural Analysis

The structural analysis was conducted in support of the design of both the full size expandable structure and the prototype test structure. The detailed coverage is presented in Reference 3. Calculated margins of safety of the critical structural components are given in Table II along with the corresponding factors of safety, loading conditions and failure modes.

Micrometeoroid Protection

A theoretical study was conducted to determine the amount of flexible

TABLE II. - SUMMARY OF THE MINIMUM MARGINS OF SAFETY

Structural Component	Minimum Margin Of Safety	Factor Of Safety	Loading Condition	Failure Mode	Comments
Meridional & Circumferential Straps					
Steel Yarns	+0.15	3.0	1-e Ultimate Internal Pressure	Tension	
Dacron Yarns	+0.71	3.0	1-e Ultimate Internal Pressure	Tension	
Strap Connections					
Steel Yarns	-0.0	3.0+1.2	1-e Ultimate Internal Pressure	Tension	
Dacron Yarns	+0.19	3.0+1.2	1-e Ultimate Internal Pressure	Tension	
Bladder	+0.88	3.0	1-e Ultimate Internal Pressure	Tension	
Terminal Ring	High	3.0	1-e Ultimate Internal Pressure	Tension	
Splices	+0.19	3.0+1.2	1-e Ultimate Internal Pressure	Tension	
Internal Packaging Rings	+0.05 +1.29	1.5 1.5	2 External Pressure 3 1-G Handling Loads	In-Plane Buckling Compressive Yielding	
Tangency Rings (Dacron Yarns)	+0.28	3.0	1-e Ultimate Internal Pressure	Tension	The steel yarn construction is not critical because of the lesser stretch
Splices	+0.09	3.0+1.2	1-e Ultimate Internal Pressure	Shear in the rivets of the sector splices	
Internal Floor Support Rings	+1.0	1.5	Ring Compression Load = 225Lb	Column Buckling of Turnbuckle	Since the initial ring radius will be changed to equal the cylinder radius, this load will probably not be obtained.
Access Hatches					
Dome	High	3.0	1-e Ultimate Internal Pressure	Tension	
Edge Ring	High	3.0	1-e Ultimate Internal Pressure	In-Plane Buckling	
Window	+0.21		1-b Proof Pressure	Flexure	
Window Reinforcement Ring	+0.97	3.0	1-e Ultimate Internal Pressure	Combined Tension and Buckling	
Spot Welds	+1.73	3.0	1-e Ultimate Internal Pressure	Shear	

foam micrometeoroid protection required to satisfy the specification of 0.995 probability of zero penetration at 200 n. mi. for 14 days. The environment criteria was that defined by Reference 4. Appropriate calculations using these parameters showed that it would be necessary to stop particles of 3.3 mg or less. In past programs, it has been found that 1.75 inches of the elastic recovery material planned for this structure is adequate to stop all stony-type particles having a mass of 3.5 mg or less. This is documented in Reference 5. The integrity of the composite relative to micrometeoroid protection is significantly related to the bumper wall used. Specimens of the composite material herewith used were furnished to LRC under this contract for subsequent micrometeoroid testing. These tests should determine whether the present outer cover is adequate, or should be altered to improve its capability to break up the particles.

Flammability characteristics of the micrometeoroid foam barrier were evaluated by simulating the fire hazard from possible micrometeoroid particle penetration and its resulting particle kinetic energy converted to heat. The temperature of a vaporizing micrometeoroid particle has been estimated as about 5400°F, the vaporizing temperature of iron. Therefore, it was decided to check the foam flammability by using a tungsten wire heated to about 5500°F. The polyether foam could not be ignited when the tungsten wire was imbedded in the foam and heated to 5500°F at an oxygen pressure of 0.10 psi and for 3 minutes duration. O_2 concentration in foam at 0.10 psi is estimated two orders of magnitude greater than the total measured leakage of the prototype model.

Thermal Analysis

A tumbling cylinder in a 200 n. mi. orbit ($k \cong 0.95$), with an orbital inclination β with respect to the earth-sun line, and an angle θ between the spin axis and the cylinder-sun line was considered.

The results are plotted in Figure 8. With random orientation the temperature is observed to be essentially constant for values of between zero and 50°, with much higher temperature for larger values of β. This is due to the decrease in albedo heating offsetting the increase in time spent in sunlight as β increases to a certain value-for β exceeding 82° the satellite is always in the sunlight. For an easterly launch from the United States, β will vary from zero to as much as 55° during a six month lifetime an α/ϵ ratio of 1.3 appears to be near optimum.

Figure 8 shows the effect of orientation on average temperatures. It is observed that orientation with respect to the sun can make a difference of ± 20°F on average temperature. Tumbling in the orbital plane is undesirable since a large β effect on temperature occurs. It would be desirable to keep θ nearly constant.

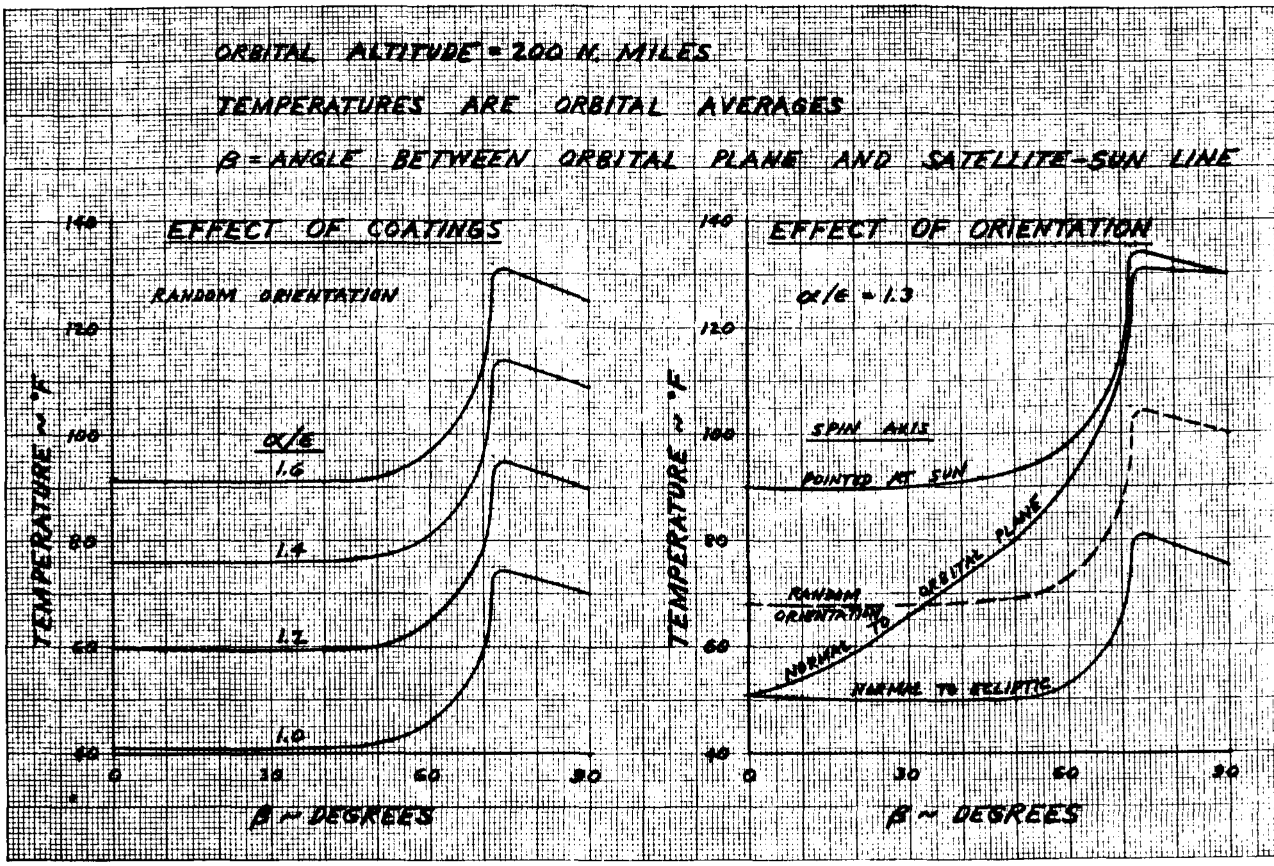

Figure 8. Temperature of tumbling cylinder

Canister Design For Prototype Testing

A canister design was prepared to support the prototype test program. The canister is a cylinder large enough to encompass the 13-foot diameter test article. Its length is approximately 2-1/2 feet.

This canister restrains the test unit longitudinally. End covers are included in the design, and for a series of packaging load tests these covers will be installed.

The test canister structure is a weldment of aluminum extrusions. A cylindrical sleeve of clear acrylic plastic is inserted into this weldment and bolted in place. This provides a smooth surface for contact with the packaged article before and during deployment tests, while at the same time allowing visual monitoring of the packaged article at all times.

FABRICATION OF PROTOTYPE MODEL

Hardware Fabrication

The hardware items include external and internal tangent rings, packaging rings, bladder terminal rings, doors, and longitudinal strap terminal rings. These items were all produced using conventional metalcraft manufacturing techniques.

Tape Manufacture Subassembly

Fifteen rolls of tape were manufactured. The yarn was taken from 28 spools, passed through a polyester resin bath with the help of special guides on either side of the bath, and onto the temporary storage drum. After curing, each full drum (900 lineal feet) was stored on a spool.

Approximately 4400 feet of this tape were subassembled to form the longitudinal straps. A number of buckle splices were required to join the 900-foot lengths. The longitudinal strap subassembly was completed prior to application to the bladder. Accurate length from terminal ring loop to terminal ring loop was controlled by subassembling over pins mounted in the floor at precise locations.

Bladder Manufacture

The manufacture of the bladder involved first, the lamination of the bladder material components into a composite material. This was followed by subassembling these panels into the proper flat-pattern shape. Next, the longitudinal strap assembly was attached to the bladder and the end gores joined. This was followed by the wrapping of the assembly into a tubular shape and splicing.

Bladder Material Lamination. - The materials available to GAC at the initiation of this program were the cloth-bilaminate film-cloth laminate, the PVC foam, and the outer layer cloth. The first operation at GAC was to laminate these materials into the pressure bladder composite (Figure 9) by vacuum bagging and oven cure. Thirty-six 3-1/2 ft x 15 ft composite bladder panels were required to make the entire bladder.

Bladder Subassembly. - Bladder panels were joined into a flat pattern on the floor area which had been specially prepared. They were laid on the floor with the film-cloth side down, and 2-inch wide film-cloth tape applied using polyester room temperature adhesive. The assembly was then inverted. Film-cloth tape was applied to the film-cloth side in the same manner. Immediately prior to putting the tape in place a 1/8-inch diameter bead of RTV Silicone was injected into the joint. The pressure of applying the tape caused

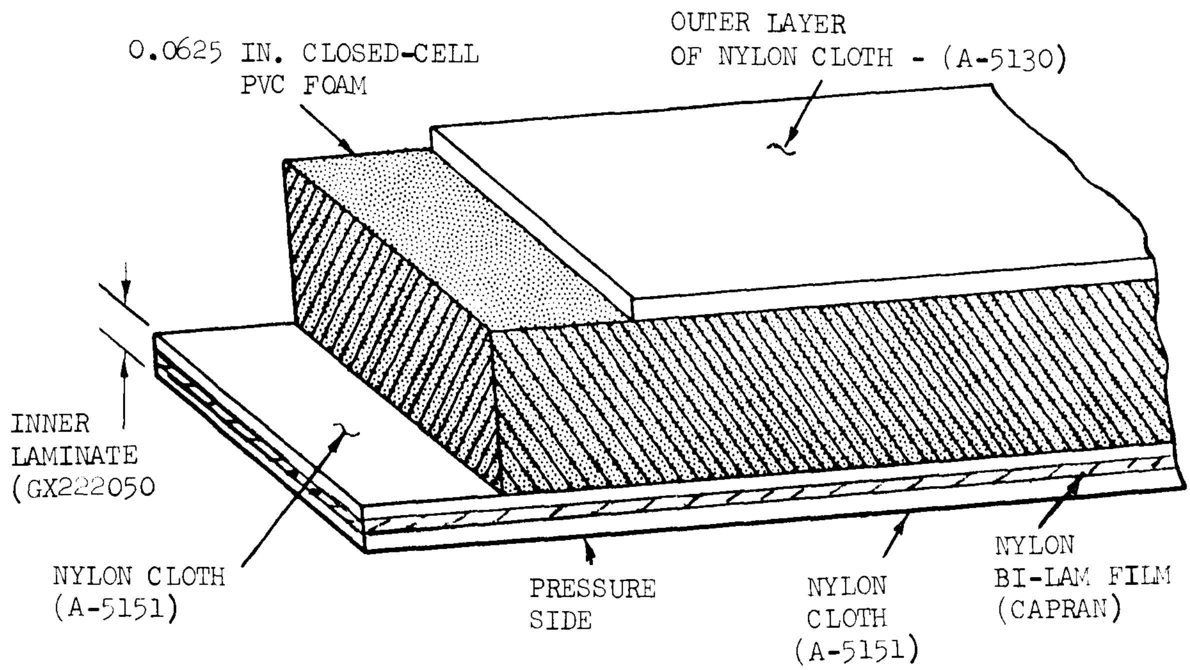

Figure 9. Pressure bladder

the silicone to flow out over the film-cloth approximately 1/4 to 3/8 inch on each side. This bonded well to the film-cloth of the panels and to the tape, resulting in an excellent seal.

It was necessary to remove excess material from the ends of this flat pattern to provide gores which could be seamed together to form the proper end contour. This is shown in Figure 10. These gores were joined and taped in the same manner as other bladder joints. Several of these gores were left unjoined while the bladder was on the floor. This permitted sufficient access to the inside to later install large hardware items such as packaging rings.

Installation of Longitudinal Strap Assembly. - The last step in the bladder assembly was that of attaching the longitudinal straps. This operation is shown in Figure 10. Attachment was made between tangent points of each strap. Locations previously marked on the straps were coordinated with the lines on the bladder. Figure 11 shows a typical area where straps are attached to bladder and a longitudinal splice. The short straps were then bonded in place for attachment of the external tangent rings.

Final Bladder Longitudinal Seam. - The bladder edges were finally brought together and the last seam made to make a tubular structure. Then the first

Figure 10. Bladder subassembly

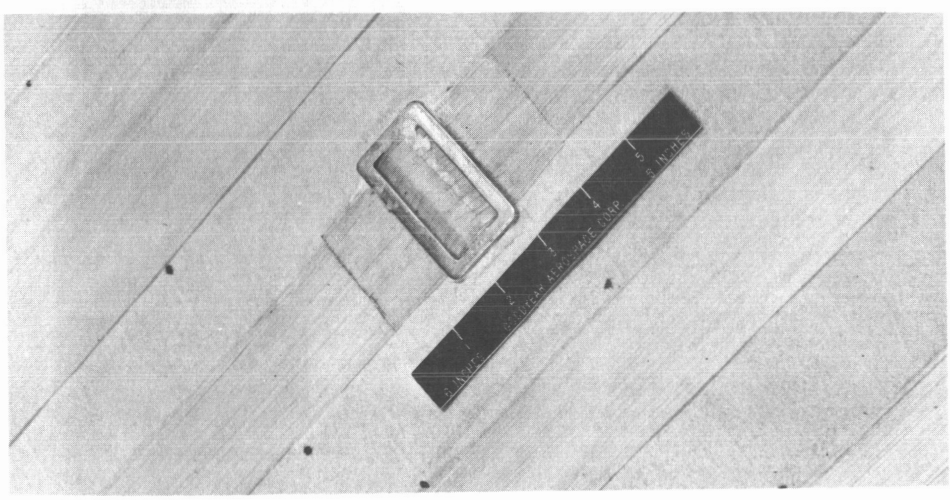

Figure 11. Longitudinal tape attachment to bladder

and last straps were joined. The bladder was hoisted into a vertical position for hardware installation. This is shown in Figure 12.

Figure 12. - Prototype model ready for hard structure

Packaging Ring. - The foam to which the packaging ring was attached was first bonded in place using polyester adhesive. The tie-strap assemblies were then bonded in place and the first packaging ring inserted through the end and tied and bonded to the ring.

Tangent Rings. - The external tangent ring was installed at the lower end. Attach straps were folded over the ring and clamped into position during cure with clamp plates and C-clamps. Epoxy adhesive was used. The lower internal tangent ring was then inserted.

Temporary Spider. - A temporary wooden spider was then inserted into the internal tangent ring. This is a fabrication aid to be removed later.

Terminal Rings. - The next step was the installation of the bladder terminal rings. First, the remaining gore seams at this end were completed. The rings were then bonded in place, again using RTV silicone for adhesion and sealing purposes. The strap terminal ring halves were then inserted through the strap loops and joined.

Temporary Door, Stub Shaft, and Handling Fixture. - The temporary door and stub shaft were installed. The handling fixture ring, and three supporting arms were then joined to the tangent ring and the stub shaft extension.

The prototype test unit was then inverted and the same procedure followed for installation of hardware and temporary fabrication aids on the other end.

Circumferential Tape Wrap. - The test article was placed in a horizontal position and the stub shafts placed in trunnion stands. This position is depicted in Figure 13. The trunnion stands provided cantilever support for the stub shaft. This left only the weight of the flexible structure between tangent rings, and the two packaging rings to be supported. The unit was then pressurized to approximately 2 inches of water. It was then stiff enough to permit removal of the handling rings and arms.

Supporting rubber-tired idler wheels were then installed to act as steady rests for turning the model during tape wrapping. This setup is shown in Figure 14. Two were placed under the tangent rings, and two under the packaging rings on each side. The wheels on one side under the tangent rings were interconnected with a common shaft. These wheels were driven by a friction pulley mounted on a variable speed drive unit.

A crude tape wrapping device was constructed, shown in Figure 14. The Dacron tape spool was mounted on the movable holder. The tape passed through a team of idler pulleys to the model. Uniform tension was maintained on the tape by a spring-loaded idler pulley.

RTV Silicone was used as the bonding agent to attach the tape to the

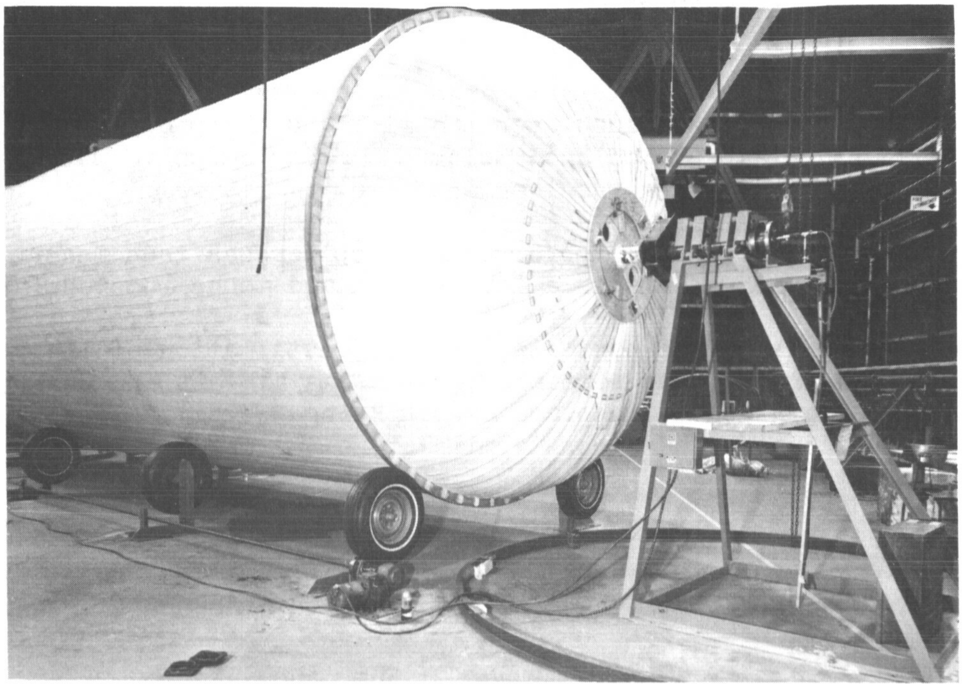

Figure 13. - Trunnion support and drive mechanism

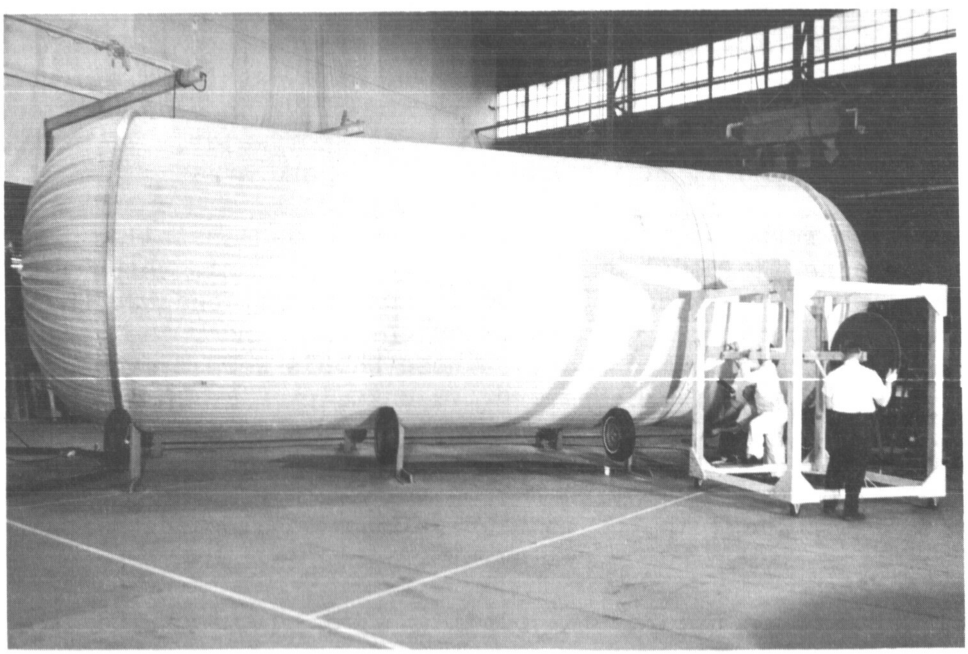

Figure 14. - Prototype model - circumferential tape installation

bladder. This material was introduced immediately ahead of the tape as it was wrapped onto the model. One complete wrap was made adjacent to one tangent ring. From that point, a spiral was followed. The tape progressed 2 inches per revolution.

Figure 14 shows this operation in progress. Figure 15 shows the operation complete. The steel bands seen in Figure 15 were used to maintain clamping pressure over buckle joints in the circumferential tapes while the joint adhesive was curing. These bands were later removed.

The last revolution of tape was parallel to the tangent ring. The tape was terminated using a buckle like those used for splices. This buckle ties the outer wrap to the last spiral wrap immediately underneath.

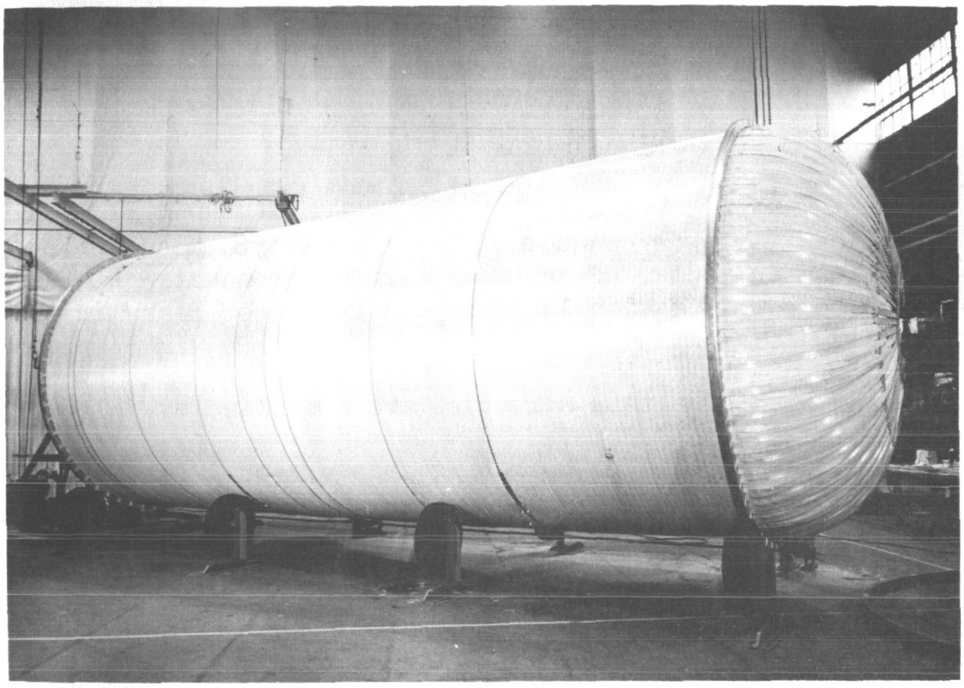

Figure 15. - Prototype model - circumferential tape wrapping complete.

Finish Door Installation. - The temporary doors and stub shafts were removed and door seals and finish doors installed.

Attachment of Longitudinal Straps. - The next task was the attachment of the longitudinal strap to the bladder in the end regions.

This was accomplished using RTV Silicone as the bonding agent. It was accomplished with a low pressure (2 inches of water) in the model.

Micrometeoroid Foam Installation. - Bleeder provisions were made on the outer surface of the structural tape to aid in evacuation of the structure wall for packaging. The entire structure from doors to tangency rings, and between tangency rings was then covered with 1-3/4 inch thick 1.2 lb/cu ft flexible open-cell foam. This is the micrometeoroid protective layer. This material was applied in slabs. Attachment was made with polyester adhesive. This adhesive was also applied to the edges of the individual slabs so that no void areas would be obtained.

Outer Cover Installation. - The nylon film-cloth outer cover was next applied. This layer provides the seal to permit evacuation of the wall for packaging. It is this surface to which the thermal coating is applied, and acts as the bumper to break up micrometeoroid particles. A complete bond was made also at the ends where the outer cover attaches to the door frame, and at the tangent rings.

PRELIMINARY LEAK TEST

A preliminary leak test was conducted on the prototype model prior to application of the foam and outer cover. The test was conducted at this stage of completion to permit easier location and repair of leaks in the bladder, if necessary.

The design requirements of this structure are specified as follows:

(1) Maximum gas leakage at operating pressure of 2 percent of total internal gas volume per 24-hour period.

(2) The operating pressure is 5 psia in a vacuum environment.

The preliminary leak test requirement specified that the expandable structure shall be inflated to an internal pressure of 1 psi and this pressure maintained for a 24-hour period to determine leak-rate characteristics.

An analysis was made to establish the permissible leak rate under the preliminary test conditions that would be comparable to the specified design requirements under the operating conditions. This is summarized as follows:

Comparing leakage to flow through an orifice with 2 percent leakage in 24 hours at 5 psia permitted, the orifice area is 0.00025 in^2 for a volume of 4350 cu ft.

If the leakage test were conducted at 5 psig on the ground, the allowable pressure decay in 24 hours would be 7.6 in H_2O. At 1 psig (ground) the allowable decay is 3.0 in H_2O. This is the target value on which to compare the preliminary leak test results.

The test was conducted with the model in the horizontal position. Three thermocouples were mounted inside, near the centerline, with one near each end and one in the center. A differential water manometer was used to measure differential pressure. Barometric readings were obtained at the start and then at the end of the test.

The internal temperature was the same at the beginning and at the end of test period, no temperature correction was necessary.

The barometric pressure increased from 28.74 to 28.78 in Hg. Correcting for this difference the final ΔP at the end of 25 hours was 24.80 in H_2O. The net loss then was 2.1 in H_2O. This was well within the 3.0 in H_2O loss permissible.

TEST PROGRAM DEFINITION

As part of this contract GAC prepared a "Proposed Test Program" report (Reference 6).

This program covers the following tests, to be carried out on the prototype model now complete.

Atmospheric Ambient Testing

- Folding and Packaging
- Gas Leak Rate
- Proof Pressure

Vacuum Chamber Testing

- Packaging Load
- Deployment
- Gas Leak Rate

After the preparation of the test program report, considerable thought was given to the testing program. It is recommended that an ultimate pressure test also be carried out at the conclusion of the other tests. This would best confirm the capability of this structure to carry out the functions structurally that have been predicted analytically and by small scale testing of material samples.

CONCLUSIONS AND RECOMMENDATIONS

The program herein reported is the initial phase of an overall program entitled "A Feasibility Investigation of Expandable Structures Module for Orbital Experiment - Artificial G".

This program included initially a design and analysis task of a full-scale structure. The results were entirely compatible with the basic structure on which the design was based. This included test evaluation of materials and material composites subsequently utilized in the design. Concurrently with this task a prototype model was designed, followed by the manufacturing of this unit. The conceptual design included utilization of fabrication techniques which are not conventional. This was necessary due to the extreme size of the product. The goal was to achieve characteristics normally common to filament wound structures, but to do so without the aid of filament winding equipment of a size to handle the complete article.

The results were quite satisfactory, and confirms that considerably larger products can be manufactured using the same basic techniques.

The assembly processes could also be applied using other materials for the structural elements. For example, stainless steel tape instead of Dacron could be readily considered. Its use would represent a penalty in weight, but the resulting structure would withstand the pressure loads equally well, with less inflation elongation due the higher modulus of elasticity. Initial tape manufacturing tasks would be somewhat slower since existing equipment used for making the tape would require some modification.

It is recommended that the test program phase be initiated as soon as possible to complete the feasibility investigation herein started. This program should cover the essentials defined by the test program developed under this contract.

It is recommended that one significant design change be made on future structures of this type. The longitudinal tapes should be 1/2 the weight of the circumferential tapes while maintaining the same width. They would then be applied side by side, with essentially no gap. This would provide complete backup for the bladder in the end regions. This is not essential, but does provide protection for the bladder at the relatively small penalty of additional adhesive weight for bonding the longitudinal straps to the bladder.

It is also recommended that some additional material optimization work be implemented. Another foam system for the micrometeoroid protection should be sought which would be more flame resistant. The adhesive system for bonding structural tape to the bladder might be investigated with significant weight reduction as the goal.

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